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# NON-LTE MODEL ATMOSPHERE ANALYSIS OF THE EARLY ULTRAVIOLET SPECTRA OF NOVA OS ANDROMEDAE 1986

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**ABSTRACT**

We have analyzed the early optically thick ultraviolet spectra of Nova OS And 1986 using a grid of spherically symmetric, non-LTE, line-blanketed, expanding model atmospheres and synthetic spectra with the following set of parameters: $5,000 \leq \mathrm{T}_{model} \leq 60,000$K, solar abundances, $\rho \propto r^{-3}$, $v_{\max} = 2000\,\mathrm{km\,s^{-1}}$, $L = 6 \times 10^4\,\mathrm{L}_{\odot}$, and a statistical or microturbulent velocity of 50 $\mathrm{km\,s^{-1}}$. We used the synthetic spectra to estimate the model parameters corresponding to the observed *IUE* spectra. The fits to the observations were then iteratively improved by changing the parameters of the model atmospheres, in particular $\mathrm{T}_{model}$ and the abundances, to arrive at the best fits to the optically thick pseudo-continuum and the features found in the *IUE* spectra.

The *IUE* spectra show two different optically thick subphases. The earliest spectra, taken a few days after maximum optical light, show a pseudo-continuum created by overlapping absorption lines. The later observations, taken approximately 3 weeks after maximum light, show the simultaneous presence of allowed, semi-forbidden, and forbidden lines in the observed spectra.

Analysis of these phases indicate that OS And 86 had solar metallicities except for Mg which showed evidence of being underabundant by as much as a factor of 10. We determine a distance of 5.1 kpc to OS And 86 and derive a peak bolometric luminosity of $\sim 5 \times 10^4$ L$_{\odot}$. The computed nova parameters provide insights into the physics of the early outburst and explain the spectra seen by *IUE*. Lastly, we find evidence in the later observations for large non-LTE effects of Fe II which, when included, lead to much better agreement with the observations.

**Key words:**
stars: abundances – stars: individual – stars: novae.

## 1 INTRODUCTION

Novae occur in binary systems where the secondary fills its Roche lobe and accretes mass onto a white dwarf primary. The accreted mass collects on the white dwarf until the temperature and pressure at the interface between the core and envelope become so great that a thermonuclear runaway (TNR) occurs. The liberation of energy from the TNR produces the nova explosion which ejects mass from the white

dwarf. If the nova ejects enough mass, the gas will be optically thick during its early evolution. Model atmosphere analyses of the optically thick nova spectra can then be used to determine many physical parameters of the nova ejecta including the energy distribution, the model temperature, the velocity structure, elemental abundances, and density distributions as a function of time. These results provide strong constraints on hydrodynamic calculations of the initial nova explosion and give insights into the physical phenomena underlying the outburst.

In this paper, we present the results of modeling of the early optically thick phase of OS And 86 (Nova Andromeda 1986) with Non-LTE (NLTE) model atmospheres. In §2, we review the basic parameters of OS And 86 and derive the reddening and distance. We do this because the determination of the reddening to OS And 86 is critical to accurately modeling the nova spectra while the distance determines the absolute properties, e.g. the luminosity. §3 discusses the *IUE* observations and the changes observed in the spectra during the early optically thick evolution. §4 reviews the PHOENIX stellar atmosphere code, including the recent addition of the NLTE treatment of Fe II and O I. We show the results of the model atmosphere synthetic spectra's fits to the *IUE* spectra in §5. The computed parameters for the best comparison of the *IUE* data is shown as a function of time to illustrate the physics of the outburst. In §6 we compare synthetic spectra calculated with Fe II in Non-LTE to those of synthetic spectra with Fe II in LTE and show that the later optically thick spectra can only be fit by synthetic spectra with Fe II in Non-LTE. Concluding remarks are presented in §7.

## 2 DETERMINATION OF THE BASIC PARAMETERS OF OS AND 1986

OS And 86 was discovered by Suzuki (IAUC 4281) on 1986 December 5. Kondo and Kosai (IAUC 4282) reported a position of $\alpha = 23^h\ 9^m\ 47.^s72$ and $\delta = +47^\circ\ 12'\ 0.''8$ (equinox 1950) corresponding to a galactic longitude of $106.^\circ05$ and a galactic latitude of $-12.^\circ12$. Observations in the ultraviolet with the International Ultraviolet Explorer (*IUE*) began on 1986 December 9, with excellent temporal coverage until the discovery of SN1987A in February 1987 limited the availability of *IUE*.

Optical maximum occurred between December 7.5 UT (Kikuchi et al. 1988) and December 8.94 UT (IAUC 4282) with an apparent visual magnitude of approximately 6.3. The ultraviolet maximum occurred between December 13.9 UT and December 16.9 UT with an integrated flux (1175 Å - 3200 Å) $\geq 6.8 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$. OS And 86 had an optical $t_3$ (the time it takes the nova's light curve to decline 3 magnitudes below maximum) of 20 ± 1 days (Kikuchi et al. 1988). This makes OS And 86 a "fast" nova according to the speed classification defined by Payne-Gaposchkin (1957). The $t_3^{uv}$ (the $t_3$ time in the ultraviolet), which is usually greater then the $t_3$ in the optical, was about 60 days (Austin et al. 1990).

Andrillat (IAUC 4289) reported broad, intense emission lines of H$\beta$ through $H_{15}$ and Fe II (multiplets 27, 28, 37, 38, 42, 43) in spectra taken on December 15 to December 21. The H$\beta$ lines showed a blue shifted absorption component with a mean radial velocity increasing from 1190 km s$^{-1}$ on December 15 to 1270 km s$^{-1}$ on December 21. This is in agreement with values obtained by Changchun et al. (1988). Based on the strong optical Fe II lines, OS And 86 was a standard Fe II (Williams 1992), or CO type nova, suggesting that the nova occurred on the surface of a white dwarf composed of carbon and oxygen.

Kikuchi et al. (1988) observed changes in the polarization properties of OS And 86 that they attribute to the formation of dust around 15 to 20 days after optical maximum. They report a 3.5 mag decrease from their observations starting 20 days after visual maximum. The photometric system used by Kikuchi et al. is transformable to the standard UBV system but only when the radiation is dominated by continuum light, i.e., at maximum light. A transformation to a standard system is impossible as the nova evolves toward an emission line dominated spectrum because the passband is narrower than the standard V filter and emission lines such as H$\alpha$ are excluded. Therefore, we have compiled a light curve for OS And 86 from the IAU circulars and AAVSO visual observation (Mattei 1995) (see Figure 1). This light curve clearly shows a dip starting in early January 1987 and lasting until mid March of 1987 when the light curve resumed its exponential decline. This dip in the light curve is a characteristic of the formation of an optically thick dust shell. This is contrary to Gehrz's (1988) assertion, based on infrared photometry, that OS And 86 is a case where no substantial dust shell developed. The strength of the dip in the V band is 1.5 ± 0.5 magnitudes. The rapid appearance of a dust shell is surprising when compared to other novae with optically thick dust shells reviewed by Gehrz (1988) and Shore et al. (1994). The dust shell in OS And 86 appeared in half the time as the one in V1370 Aql, a very fast ($t_3$ = 10 days) nova and 1/3 the time of the slow novae FH Ser and LW Ser ($t_3$ = 67 and 55 days respectively).

### 2.1 Extinction and Reddening corrections

The determination of the external reddening and interstellar extinction curve for OS And 86 is necessary for accurately modeling the spectra. Due to the poor response of the LWP camera on the *IUE* satellite between 2000 and 2300 Å, the 2175 Å feature cannot be used to determine the reddening. This wavelength region was also noisy in later optically thin spectra. There are, however, other ways to determine the amount of reddening of a nova and we summarize them here:

(1) From a literature search for all galactic classical novae with UBV photometry, Van den Bergh and Younger (1987) determined that the intrinsic color of a nova at $t_2$ (the time to fall 2 magnitudes) is $(B\text{-}V)_o$ = -0.02 ± 0.04 magnitudes. Milani et al. (IAUC 4306) report a (B-V) of +0.25 at $t_2$ corresponding to an E(B-V) of +0.27 ± 0.04.

(2) The intrinsic color index of classical galactic novae at maximum is given by Allen (1973) to be $(B\text{-}V)_o^{max} \approx 0.2$. Krisciunas et al. (IAUC 4282) report a value of $(B\text{-}V)^{max}$ = +0.41 on December 9.3, 1986 (UT) which implies an E(B-V) of 0.21 magnitudes.

(3) Miroshnichenko (1988) analyzed the UBV photometry of more than 20 novae and found that the time almost immediately after maximum light, when the color index remains approximately constant (called the "stabiliza-

tion stage") can be used to find E(B-V). The average for novae in Miroshnichenko's study is $(B\text{-}V)_o$ = -0.11 ± 0.02 during the stabilization stage. From IAU circulars and the photometry of Kikuchi et al., we estimate that this stage started around Dec. 18th (UT) and continued for 10 days. The average (B-V) during this time is 0.23 magnitudes, implying an E(B-V) = 0.34.

(4) A different approach is to analyze line of sight extinction toward stars or galaxies in the direction of the nova. Austin et al. (private communication) used the color excess map compiled by Burstein and Heiles (1982) to show that OS And 86 lies in a region where E(B-V) = 0.24 magnitudes. The color excess map is a combination of galactic and extragalactic reddening and *does not* include any circumstellar extinction .

The mean reddening of the four values is 0.26 magnitudes. For OS And 86, therefore, we adopt an estimate of E(B-V) = 0.25 ± 0.05.

## 2.2 Absolute Magnitude and Distance Determination

A determination of the distance is essential for determining absolute properties of a nova. A great deal of effort has been expended on determining $M_V$, and thus the distance, of novae from samples of novae with independently known distances. A compilation of maximum magnitude versus the rate of decline (MMRD) relationships is published in Chochol et al. (1993) for V1974 Cyg 1992. The relations are:

(1) $M_{0,V} = -10.70 + 2.41 \log(t_2)$ (Cohen 1985),
(2) $M_{0,V} = -7.89 - 0.81 \arctan((1.32 - \log(t_2))/0.19)$ (Capaccioli et al. 1989),
(3) $M_{0,V} = -11.75 + 2.5 \log(t_3)$ (Schmidt 1957),
(4) $M_{15,V} = -5.6 \pm 0.14$ (Cohen 1985),
(5) $M_{15,V} = -5.23 \pm 0.39$ (van den Bergh and Younger 1987),

where $M_{0,V}$ and $M_{15,V}$ are the absolute V magnitudes at maximum and 15 days after maximum, respectively. OS And 86 had a $t_2$ of 8 ± 1 days. The mean absolute magnitude at maximum light from the first three methods is $M_{0,V} = -8.6$. If we assume an extinction of $A_v$ = 3.1E(B-V) = 0.78, then the distance to OS And is 6.6 kpc. A visual inspection of the lightcurve shows that OS And 86 had V ≈ 9 mag fifteen days after optical maximum. Using the same extinction as before and the mean $M_{15,V}$ from the last two methods, we find a distance to OS And 86 of 5.3 kpc.

The MMRD relationships depend on a statistical fit to surveys containing different composition classes and different speed classes of novae. These methods work well in determining an *average* relationship for all novae in the sample but when applied to an *individual* nova they cannot be very accurate because of the large spread in the properties of individual novae.

There is another approach to determine the distance to novae which is *not* based on statistical methods (Starrfield et al. 1992a). We require a similar nova at a known distance and with a known extinction and reddening. Novae in the LMC are a good choice because 7 different novae have been observed in the LMC with *IUE*, it is at a well established distance, and the extinction and reddening to the LMC is small. One fast CO type LMC nova, LMC 1992 (hereafter LMC 92), exhibited an outburst very similar to OS And 86, with the exception that LMC 92 was faster with $t_3$ = 16 ± 2 days. We have obtained an *IUE* composite spectrum of LMC 92 on Nov. 20, 1992 (SWP46299+LWP24328) at approximately the same stage of spectral development as OS And 86 on Dec. 13, 1986, (see Figure 2). The LMC 92 spectrum displays most of the same features and mimics the shape of the pseudo continuum of OS And 86. If we assume that the UV luminosity of OS And 86 was the same as LMC 92 at this epoch, then the distance to OS And 86 is given by:

$$D_{OS} = D_{92}\sqrt{\frac{f_{92}}{f_{OS}}},$$

where $f_{92}$ and $f_{OS}$ are the total dereddened UV fluxes (1175 Å to 3300 Å) of LMC 92 and OS And 86 respectively, (dereddened with an E(B-V) of 0.15 ± 0.05 and 0.25 ± 0.05). Gould (1995) reports a value of 47.3 ± 0.8 kpc to the centre of the LMC. We allow an additional ± 500 pc due to the uncertainty in the location of LMC 92 within the LMC and adopt $D_{92}$ = 47.3 ± 1.3 kpc. The total observed UV flux of LMC 92 and OS And 86 are $3.9 \pm 1.7 \times 10^{-10}$ and $3.3 \pm 1.3 \times 10^{-8}$ ergs $s^{-1}$ $cm^{-2}$, respectively. Using the flux ratio we determine a distance of 5.1 ± 1.5 kpc. Here the dominant source of error is the uncertainties in the reddening. This distance places OS And 86 at a distance of 1.1 ± 0.3 kpc below the galactic plane. This is outside the galactic disk and suggests that OS And 86 is not from the young disk population.

Using the distance determined from this technique we find that OS And 86 had $M_{0,V} = -8.0 \pm 0.7$. The mass of the underlying white dwarf can then be estimated from the formula derived by Livio (1992):

$$M_{WD} \approx 10^{\left(\frac{-8.3-M_{0,B}}{10.0}\right)},$$

where $M_{0,B}$ is the absolute B magnitude at visual maximum and $M_{WD}$ is the mass of the white dwarf in solar masses. The equation is an approximation since it is only a function of the absolute B magnitude and it neglects effects such as the white dwarf's luminosity, magnetic field, the mass accretion rate, and the composition of the accreted material. Nevertheless, Livio's equation gives an estimate of the white dwarf mass of 0.9 ± 0.2 $M_\odot$. Table 1 summarizes the basic parameters of OS And 86.

# 3 OBSERVATIONS

We have retrieved high and low resolution archival *IUE* spectra of OS And 86 obtained with the long wavelength primary (LWP: 2000-3300 Å) and the short wavelength primary (SWP: 1175-1950 Å) cameras. These spectra were reduced at Goddard Space Flight Center (GSFC) Regional Data Analysis Facility (RDAF) using the standard *IUE* software and special purpose IDL routines.

*IUE* took 3 high ($R = 10^4$) dispersion spectra and 29 low (R ≈ 300) dispersion spectra of OS And 86 during the first month after discovery while the nova atmosphere was still optically thick. Unfortunately, not all of these spectra are suitable for analysis. Due to the *IUE* satellite's small

dynamic range, some spectra have their strongest features overexposed, while some shorter exposure spectra underexpose the weakest regions. On a few days, two low resolution LWP and SWP spectra were taken within one hour of each other. One of each low resolution pair was a long exposure while the other two were short exposures. This was done to compensate for the limited dynamic range of *IUE*. Therefore, we combined the best exposed portions of each spectrum to provide a final spectrum for that particular time. Table 2 gives the dates on which suitable low resolution *IUE* spectra exist and the image numbers and exposure information of each spectrum.

The optically thick phase of a nova outburst can be divided into three distinct phases. These are the "fireball" phase (Gehrz 1988, Shore et al. 1993), the "continuous mass loss" phase (Hauschildt et al. 1994), and the "pre-nebular" phase.

The "fireball" is the first stage in a nova's development and marks the phase when the ejected material is adiabatically expanding and cooling from very high initial temperatures. The cooling of this optically thick material shifts the flux peak from the UV to optical wavelengths and causes a steep decline in the ultraviolet. Because the fireball ejecta become optically thin before maximum light in the V band, it is difficult to obtain spectra during this relatively rapid phase of development of the nova. Only for novae discovered very early during the rise to maximum in V, such as V1974 Cyg (Hauschildt et al. 1994; Shore et al. 1993) and Nova LMC 1991 (Schwarz et al. in preparation), have this interesting "fireball" phase been observed. OS And 86 was probably just past the fireball phase at the time of the first *IUE* observations.

The fireball ejecta become progressively more transparent and the deeper layers of the nova atmosphere become visible as the optical flux passes through maximum. Previous work (Hauschildt et al. 1994, 1995a) on Nova Cas 1993 has shown that nova atmospheres have sufficient radiation pressure to drive mass loss at this epoch while the optical emission lines show strong P-Cygni profiles, indicative of a continuous outflow. We, therefore, term this the "continuous mass loss" phase. It is around this time that the "iron curtain" comes to dominate the spectrum. The temperature drop from the "fireball" phase causes higher ions to recombine, which in turn causes a large increase in UV opacity. This explains why the "continuous mass loss" phase is characterized by a pseudo-continuum created by overlapping absorption lines, mainly Fe II. The pseudo-continuum peaks strongly at longer wavelengths ($\approx$ 3000 Å) with almost undetectable flux at the shorter wavelengths where the opacity is largest.

The first two spectra in Figure 3 and Table 2 show OS And 86 in this early "continuous mass loss" phase. These spectra are very similar in appearance except that the integrated flux is about 30% higher on Dec. 11. There is almost no flux shortward of 1500 Å on either day. The spectra are dominated by features that appear to be emission lines, but these "lines" are in reality *regions of transparency where the opacity is reduced.* The features between 2600 Å and 2700 Å, and between 2900 Å and 3000 Å, are gaps in the Fe II line absorption (Hauschildt et al. 1994). Mg II 2800 Å (and possibly Al III 1860 Å) is the only true emission line which is present during this epoch and it is strongly blended with Fe II lines.

As this phase progresses, the overall slope in the ultraviolet spectra evolves so that the pseudo-continuum gradually appears to flatten. The drop in density from the expansion causes a decrease in line opacity in this spectral region. This "lifting of the iron curtain" (Hauschildt et al, 1992b, 1994, Shore et al. 1994) causes the flux peak to gradually shift into the SWP region of the spectrum (see §5).

The "lifting of the iron curtain" in OS And 86 is shown in the middle two spectra in Figure 3 and in Table 2. These spectra show an increase of about a factor of 3 in integrated flux below 2000 Å with respect to the first two spectra. The increase is so great that the spectrum above 1700 Å is overexposed on Dec. 16th. The dramatic increase in the SWP region and the slight increase in total integrated flux of the LWP give the impression that the spectra have flattened. Table 2 shows that at this time OS And 86 reached its maximum in the UV. This is directly attributable to the increase in radius of the ejected gas and subsequent drop in Fe II opacity.

The "pre-nebular" phase is characterized by the emergence of moderately ionized ($\lesssim$ 54 eV ionization potential from the presence of He II), allowed, semi-forbidden, and forbidden emission lines superimposed on a pseudo continuum that is peaked toward the blue. These lines are formed in the outer region of the atmosphere where the density is sufficiently low for nebular emission lines to appear. As the opacity continues to drop, these lines strengthen and the spectra begin to resemble those obtained during the optically thin "nebular" phase of other novae.

The last 2 spectra in Figure 3 and Table 2 show this phase in OS And 86. Their psuedocontinua are strongly sloped to the blue and are dominated by pre-nebular lines. The strongest of the lines are due to O I, N I, He II, C II, N II, Mg II, and N III. A complete list of the pre-nebular lines is given in Table 3. At this phase, the strongest lines are from CNO ions with low ionization states such as O I (1304 Å), C II (1335 Å), and N III (1750 Å). In addition, there is evidence of emission lines to the metastable $^2P^0$ and $^2D^0$ states of N I during this phase. The strongest emission lines from N I (Moore 1993) are:

(1) 3d($^2$D) - 2p$^3$($^2$P$^0$) at 1310 Å,
(2) 3d($^2$P) - 2p$^3$($^2$P$^0$) at 1319 Å,
(3) 3s($^2$D) - 2p$^3$($^2$P$^0$) at 1411 Å,
(4) 3s($^2$P) - 2p$^3$($^2$P$^0$) at 1743 Å,
(5) 3s($^2$D) - 2p$^3$($^2$D$^0$) at 1243 Å and,
(6) 3s($^2$P) - 2p$^3$($^2$D$^0$) at 1493 Å.

Figure 4 shows the N I emission lines in the Dec. 27th high resolution UV spectrum, SWP29981. The line at 1319 Å is clearly seen while the line at 1310 Å is blended with O I 1304 Å (Figure 4a). Interstellar absorption lines of O I and C II 1336 Å can also be seen. In Figure 4b, the line at 1411 Å is blended with an unidentified line at 1415 Å. The O IV] and Si IV] lines around 1401 Å are present but weak and severely blended. The location of the line centre in Figure 4c indicates that the strong line near 1486 Å is *not* N IV but rather N I at 1493 Å (see Scott et al. 1995). The C IV line at 1550 Å is present but is also weak. In Figure 4d, the N III] line at 1750 Å is clearly blended with the N I line at 1743 Å.

## 4 MODEL ATMOSPHERES

### 4.1 Model construction

The spectral syntheses of the early spectra of OS And 86 were calculated using the method described by Hauschildt and Baron (1995b). Therefore, here we provide only a brief description of the method and summarize the recent changes to Hauschildt's non-LTE, expanding, stellar atmosphere code PHOENIX.

PHOENIX solves the special relativistic equation of radiative transfer (SSRTE) in the Lagrangian frame self-consistently with the multi-level, non-LTE rate equations and the special relativistic radiative equilibrium (RE) equation in the Lagrangian frame. Numerical methods used in PHOENIX include the following: (i) the solution of the SS-RTE is done using the operator splitting method described by Hauschildt (1992a), (ii) the RE equation is solved by an Unsöld-Lucy type temperature correction scheme (Allard 1990), and (iii) the multi-level non-LTE continuum and line transfer problem is treated using the operator splitting method described by Hauschildt (1993).

The following species are treated in non-LTE: H I (10 levels), Mg II (18 levels), Ca II (5 levels), Ne I (26 levels), and O I (36 levels) (Hauschildt et al 1994). The lines are represented by depth-dependent Gaussian profiles with 25 wavelength points per permitted non-LTE line.

A recent addition to the PHOENIX atmosphere code is a fully non-LTE treament of Fe II. This ion plays an important role in the formation of early nova spectra because of its high abundance and low ionization threshold. We used an Fe II model atom that includes 617 levels, over $10^4$ primary permitted transitions, and over $10^6$ secondary transitions (Hauschildt and Baron 1995b; Hauschildt et al. 1996). Its inclusion considerably alters our synthetic spectra and dramatically improves the fits to the *IUE* data when compared to LTE treatments. This will be demonstrated in §6.

In addition to the non-LTE lines, the models self-consistently include line blanketing by the most important ($\approx 10^6$) metal lines selected from the Kurucz (1994) line list. The entire list contains close to 42 million lines; however, not all of them are important for a particular nova model. Therefore, before each temperature iteration, a subset is selected from the original list by a process described in Hauschildt et al. (1992b, 1994). We treat line scattering in the metal lines of LTE species (approximately) by parameterizing the albedo for single scattering, $\alpha$. The detailed calculation of $\alpha$ would require a full non-LTE treatment for *all* lines and continua, which is outside of the scope of this paper. Tests have shown that the line profiles do not depend sensitively on $\alpha$ as a direct result of the velocity gradient in nova photospheres and that our approach is reasonable. An average value of $\alpha = 0.95$ is used; recent results indicate that this is an acceptable choice (Hauschildt and Baron 1995b). The continuous absorption and scattering coefficients are calculated using the species and cross sections described in Hauschildt et al. (1995a) and Allard and Hauschildt (1995).

### 4.2 The model parameters

The model atmospheres are characterized by the following parameters (see Hauschildt et al. 1992b for details):

(1) the reference radius $R$, which is the radius where either the continuum optical depth in absorption or extinction at 5000Å is unity,

(2) the model temperature $T_{model}$, which is defined by means of the luminosity, $L$, and the reference radius, $R$, ($T_{model} = (L/4\pi R^2\sigma)^{1/4}$ where $\sigma$ is Stefan's constant),

(3) the density parameter, $N$, ($\rho(r) \propto r^{-N}$),

(4) the maximum expansion velocity given by $v = \dot{M}/4\pi r^2\rho$ with the mass loss rate, $\dot{M}$(r), assumed to be a constant,

(5) the density, $\rho_{\rm out}$, at the outer edge of the envelope,

(6) the statistical velocity $\xi$, treated as depth-independent isotropic turbulence, and

(7) the element abundances.

We emphasize that for *extended* model atmospheres, one should not assign a physical interpretation to the parameteric combination of $T_{model}$ and $R$. Previous work (Hauschildt et al. 1992b, 1994, 1995a) has called the model temperature an "effective temperature", or $T_{eff}$, but this is technically not correct. In plane-parallel stellar atmospheres, it is possible to define an effective temperature as the temperature of a black body emitting the equivalent flux. However, in an extended atmosphere there is no longer a *unique radius* at which this can be defined. By using a reference radius at a prescribed *continuum* optical depth scale at $\lambda = 5000$Å we define a model temperature. We emphasize that *the model temperature must be regarded only as a convenient numerical parameter used to describe the model and is not directly comparable to any observationally determined radius except at 5000 Å.* Pistinner et al. (1995) present a detailed discussions of nova atmosphere parameterization.

## 5 RESULTS OF NLTE MODELING

The parameters that affect the synthetic spectra most sensitively are the model temperature, the density parameter, and the metal ($Z > 2$) abundances. Previous work (Hauschildt et al. 1992b: Hauschildt et al. 1994) and hydrodynamic calculations of nova outbursts (Starrfield et al. 1992b) have shown that the post optical maximum optically thick phases are best modeled with $N \approx 3$. With N fixed at 3, we created three libraries of synthetic spectra where only the model temperature was varied. Each library consisted of models with metal abundances (by number) of 0.5, 1, and 2 times the solar value. We did this for two reasons. The metal rich synthetic spectra were calculated because nova theory predicts that metals (namely CNO) should be enhanced relative to hydrogen because of mixing of accreted material with core white dwarf material (Politano et al. 1995). To investigate the possibility that the secondary star of OS And is a metal poor subdwarf since it lies outside the galactic disk, we created the metal poor synthetic spectra.

A maximum velocity of $v_{max} = 2000$ km s$^{-1}$ was chosen as a reasonable guess for a typical nova, while a statistical velocity of $\xi = 50$ km s$^{-1}$ was chosen as a typical value for hot stars. The model's luminosity was chosen as $6 \times 10^4$ L$_\odot$ (see section §2.2). The outer pressure, $\rho_{\rm out}$, was set to $10^{-3}$ dyn cm$^{-2}$ to ensure that the material above the model atmosphere was optically thin at all wavelengths. The synthetic spectra were convolved with a gaussian kernel with 5 Å resolution to simulate the low resolution *IUE* spectra.

In Figure 5, we show a collection of synthetic spectra compared to the *IUE* spectrum of Dec. 11th. Figures 5a,b, and c show the best fitting synthetic spectrum with the metal rich, solar, and metal poor abundances, respectively. Notice that increasing the metallicity (Figure 5a) produces a spectrum that has a higher model temperature (19000 K) than the solar abundance synthetic spectrum (17000 K: Figure 5b) which in turn is hotter than the metal poor synthetic spectrum (16000 K: Figure 5c). We will explain this phenomenon shortly and describe how it can be used to determine the model temperature of the nova.

Although these three synthetic spectra fit the *IUE* spectrum well at most wavelengths, below 1500 Å they predict about 100 times the observed flux. In principle, this region of the spectrum can be used to determine the CNO abundances because of the large opacity from the numerous CNO lines located below 1500 Å. Increasing the CNO abundance reduces the flux in the synthetic spectra in this spectral region. However, our LTE treatment of CNO does not significantly improve the fits of the synthetic spectra with CNO abundances greater than 10 times solar. An accurate analysis of this spectral region requires that all CNO ions be treated in NLTE which is currently being implemented. Therefore, we *cannot* presently say by how much the CNO elements may be overabundant.

Most of the spectral features are reproduced by the synthetic spectra in the region between 1500 and 2600 Å. The flux in the synthetic spectra is generally too low by as much as 40% between 2300 and 2600 Å. We *stress* that in this region, it is only important for the synthetic spectra to show the same features as seen in the *IUE* spectrum and *not* to precisely reproduce the flux. This is because the exact shape of the interstellar extinction curve, particularly the strength of the 2175 Å absorption feature, is not known for OS And 86.

The features above 2600 Å, caused by the gaps in the distribution of iron peak absorption lines, are well fit by all of the synthetic spectra. All three synthetic spectra predict too much flux at Mg II (2800 Å). A synthetic spectrum with the magnesium abundance (relative to solar) *reduced by a factor of 10* was found to substantially improve the fit to the Mg II emission line. Because of the strength of this resonance transition we cannot determine the magnesium abundance with high precision, but it seems likely that magnesium is depleted relative to hydrogen; possibly by as much as a factor of 10 (from a solar abundance).

The reason that all three synthetic spectra exhibit a good comparision to the *IUE* data is the relative insensitivity of the iron curtain to the details of the model. In Figure 6a, we plot the metal rich synthetic spectrum with a model temperature of 17000 K (dotted line) and a solar metallicity synthetic spectrum with the same model temperature (solid line). The higher metallicity spectrum shows stronger metal lines, mostly Fe, in the optical as compared to the solar metallicity spectrum. However, in the UV, the presence of the iron curtain implies that a synthetic spectrum with larger metal abundances has an increased opacity. This produces a steeper UV pseudo continuum, which can be seen in the flux ratios. In order, to produce a UV synthetic spectrum which resembles the solar metallicity spectrum at 17000 K (dotted line) but using a higher metallicity, we must increase the model temperature by 2000 K (solid line: see Figure 6b). The depopulation of Fe II by the hotter radiation field is balanced by the increase in Fe abundance. Even though different combinations of model temperature and metallicity produce UV spectra that are qualitatively similar, Figure 6b shows clearly that the optical continuum *relative* to the UV is very different between the two spectra. Unfortunately, there are no flux calibrated optical spectra for OS And 86 during the optically thick epoch to help us determine the metallicity. This underscores the need to have flux calibrated *optical* observations together with the UV for novae.

We cannot presently say which of the three synthetic spectra is most representative of OS And 86 (from this *IUE* spectrum alone), since the comparisons are essentially the same in these low resolution *IUE* spectra. To resolve the ambiguity, we used high resolution *IUE* spectra. In Figure 7, we show the *IUE* high resolution spectrum (LWP9719 (2400 to 2780 Å) + LWP9717 (2780 to 3200 Å)) of December 16th, 1986 as a dashed line to facilitate viewing. Figures 7a,b, and c show the best fitting synthetic spectra with 2 ($T_{model}$=20000K), 1 ($T_{model}$=20000K), and 0.5 ($T_{model}$=19000) times solar metallicities respectively (solid line). The twice solar synthetic spectrum produces absorption features between 2850-2900 Å and between 2950-3250 Å that are stronger than observed. The Fe II absorption in the wing of Mg II, at 2750 Å, is too weak, the flux predicted blueward of 2600 Å is too low, and the flux longer then 3250 Å is too high, compared to the *IUE* spectrum. These results force us to abandon the high metallicity models for OS And 86.

The other two synthetic spectra fit most of the features fairly well and reproduce the flux throughout the *IUE* spectrum except for the Mg II 2800 Å line. We suspect that at this epoch the Mg II line includes an additional component from the outermost optically thin regions of the atmosphere. This component is not currently included in the model calculations and an analysis of Mg II at this epoch would have to account for this "pre-nebular" contribution. A careful examination of Figures 7a and b shows that the synthetic spectrum with solar metallicities gives a slightly better fit. The features at 2550 Å, 2610 Å, 2675 Å, and the flux redward of 3000 Å are in better agreement with the observed *IUE* spectrum. Although we adopt the synthetic spectra library with solar metallicity for the rest of the discussion, we point out that the metal poor model is not inconsistant with the *IUE* data alone.

### 5.1 Time development of the model atmosphere

Each model atmosphere calculates nova properties at 50 logarithmically spaced depth points between $\tau_{std} = 10^{-6}$ and $\tau_{std} = 10^{4}$, where $\tau_{std}$ is the optical depth of the continuum at 5000 Å. We use the information contained in the $\tau$ grids, from the best fit model atmospheres, to illustrate the physics in optically thick UV nova spectra.

The optical depth, electron temperature and density are presented at a fixed radius of $10^{13}$ cm as a function of time in Figures 8a, b, and c. The figures show that as the nova evolves, the optical depth decreases, the electron temperature increases, and the density drops at this radius. The interpretation is that as the nova expands, the density drops and the deeper, hotter layers are exposed. The outer lay-

ers decrease in density due to expansion and are exposed to a hotter radiation field allowing the strong "pre nebular" emission lines to appear superimposed on top of the pseudo continuum.

The "lifting" of the iron curtain is illustrated in Figure 8d. This Figure shows the Fe II number density as a function of time at $\tau_{std} = 1$ in the solar abundance model atmosphere. During the earliest epochs of the "continuous mass loss" phase, the number density of Fe II is high, which produces the increased opacity in the UV spectrum. The Fe II number density falls rapidly during expansion, which is manifested in the observed UV spectra as a flux increase in UV.

In Figure 8e, we show the bolometric flux. It has been shown (Hauschildt et al. 1995a) that the synthetic spectra are insensitive to the luminosity of the model atmosphere and thus we cannot determine the luminosity from the synthetic spectra alone. We can find the bolometric flux of OS And through another method. First, we note that the synthetic spectrum, which best fits each *IUE* spectrum, includes regions outside the wavelength regime of *IUE*. By summing the flux in each synthetic spectrum, we arrive at a bolometric flux for each epoch of the *IUE* data. The plot shows that the flux was constant, within the limits of our error, for about the first week after visual maximum when it then declined. This decline is due to the presence of strong pre-nebular emission lines in the UV and the optical (Changchun et al 1987) beginning in late December. Since these lines are not included in the synthetic spectrum's bolometric flux, and are a significant contribution to the flux (of order 10% in the UV alone), the last two data points are only lower limits. Using the distance determined in §2, the bolometric luminosity of OS And 86 is $5 \pm 2 \times 10^4$ $L_\odot$ or about the Eddington limit for a 1 $M_\odot$ white dwarf. This is in agreement with the white dwarf mass derived in §2.

In addition, the constant bolometric flux of the early optically thick nova is consistant with the reddening determined in §2. If the luminosity is constant, then the maximum integrated flux in the optical is equal to the maximum integrated flux in the UV. We use photoelectric B and V magnitudes, converted to fluxes using Allen (1973), on 1986 December 9.34 (IAUC 4282) to approximate the maximum integrated optical flux. The maximum integrated UV flux is equal to the maximum optical flux when E(B-V) $\approx$ 0.25.

## 6 FE II NLTE VS FE II LTE

In LTE models, the occupation numbers, the opacity, and the emissivity are assumed to be locally in thermodynamic equilibrium throughout the atmosphere. Generally, while the assumption of LTE should be acceptable in stars, an accurate treatment for nova atmospheres demands that the most important species be treated in NLTE. This is because nova atmospheres have large temperature and density gradients, low densities, and highly non-Planckian radiation fields and thus *must* exhibit non-LTE behavior.

Fe II LTE model atmospheres with model temperatures $\approx$ 17,000 K produce synthetic spectra that are very similar to their NLTE model counterparts. At this model temperature, the departures from LTE are not significant (see Hauschildt et al. 1996). However, in hotter models, the NLTE effects in Fe II are considerable. The hotter radiation field prevents the recombination of Fe III to Fe II, thus decreasing the Fe II abundance. Figure 9a and b give the LTE (triangles) versus the NLTE Fe II (diamonds) number density as a function of optical depth for the best fit synthetic spectra on Dec. 11th ($T^{LTE}_{model} = T^{NLTE}_{model} = 17000$ K) and Dec. 27th ($T^{LTE}_{model} = 27000$ K and $T^{NLTE}_{model} = 25000$ K). The cooler model atmospheres show essentially the same Fe II abundances in the outer atmosphere regardless of the way Fe II is treated. In the hotter models, however, the LTE model shows a severe overabundance of Fe II, by as much as $10^3$, in the outer regions of the atmosphere. The consequences of the increased Fe II number density can be seen in the synthetic spectra.

In Figure 10a and b, we show the Dec. 27th *IUE* spectrum compared to the solar abundance synthetic spectrum from the model atmospheres used in Figure 9b. The strong allowed, semi-forbidden, and forbidden lines in the spectrum arise from the optically thin ejecta beyond the largest radii considered in the model atmospheres. The pseudo-continuum is well reproduced by both synthetic spectra but the LTE spectrum shows very strong Fe II emission lines at 2410 Å, 2640 Å, and 2780 Å (Figure 10a). The Fe II emission in the wing of the Mg II 2800 Å produces a very strong line which equals the intensity of Mg II observed in OS And 86. The NLTE synthetic spectrum shows none of these Fe II emission features and a weak Mg II line in Figure 10b. The Mg II line is further reduced in strength if the model atmosphere is reduced in magnesium abundance by a factor of ten. Additional Mg II emission is produced from the optically thin ejecta beyond the outer model radius. In order to produce the features in the pseudo continuum seen in the IUE spectrum, Fe II *must* be treated in NLTE. The LTE models overpopulate Fe II resulting in very strong Fe II lines that are not observed in the IUE spectrum.

## 7 SUMMARY

OS And 86 was a fast CO type nova whose ejecta were optically thick in the UV for about one month after visual maximum. This fact, along with the early *IUE* coverage, makes it an ideal candidate to determine the chemical composition and physical conditions in the early nova outburst by using a model atmosphere analysis. In order to accurately model the data, we require the reddening. The 4 different methods used in this study give E(B-V) = 0.25 $\pm$ 0.05 as the reddening to OS And 86. To determine the absolute properties, such as the luminosity, we have derived a distance to OS And 86 of 5.1 $\pm$ 1.5 kpc. At this distance and at a galactic latitude of -12.°1 OS And 86 is $\geq$ 1 kpc below the galactic disk.

To model OS And 86 we created three synthetic spectral libraries (varying only the model temperature) with different abundance sets. As a starting point, the first library contains solar abundance synthetic spectra. Because of OS And 86's location in the galaxy and to investigate the possibility that OS And 86 may be a member of the metal poor halo population, the second library consists of metal poor synthetic spectra. Since earlier studies of Nova V1974 Cyg 1992 and Nova V705 Cas 1993 (Hauschildt et al. 1994a, 1994b) reported enhancements of the metals C,N,O and Fe relative

to hydrogen we produced a set of metal rich synthetic spectra for the last library.

The *IUE* spectra are best fit by synthetic spectra with solar metallicities although we can not rule out the metal poor synthetic spectra with the *IUE* data alone. The fact that we do not find evidence for a metal enhancement is puzzling since theory predicts that CNO elements should be enhanced relative to hydrogen caused by the mixing of white dwarf core material with accreted material (Starrfield 1989). Further, the synthetic spectra are in better agreement at 2800 Å when the Mg abundance is decreased from solar by an order of magnitude in all models. A possible explanation is that the secondary star of OS And 86 is a galactic halo subdwarf. A subdwarf would provide metal poor material that was accreted onto the white dwarf. Mixing with the white dwarf core would enhance the CNO elements but leave the high Z metals, e.g. Mg, Fe, etc., essentially unchanged. Unfortunately, we were not able to determine the CNO elemental abundances very accurately, but the "pre-nebular" spectra show strong line emission from the CNO elements indicating that these elements are overabundant with respect to solar. We have shown that treating other elements, namely Fe II, in NLTE significantly improves the fits to the *IUE* spectra. Future work will include a more accurate determination of the CNO abundances using model atmospheres with CNO in NLTE (Hauschildt et al. 1996)

The model atmospheres give insight into the physical conditions of the outburst. During the "continuous mass loss" phase, the models show that the atmosphere is relatively "cool" and dense while the Fe II abundance is high. The synthetic spectra show, and the *IUE* spectra confirm, that the spectra at this epoch are dominated by Fe II absorption. As the nova shell expands, the electron temperatures rise and the electron densities drop at a fixed location in space. The density and opacity drop due to expansion and the ejecta outside the model atmosphere are now exposed to a hotter radiation field. This leads to the formation of the "pre-nebular" lines seen super-imposed on the hot pseudo-continuum in the *IUE* spectra.

The model atmospheres also provide the bolometric flux. We use synthetic spectra to determine the flux of OS And 86 at all wavelengths and our derived distance to obtain a bolometric luminosity of $5 \pm 1 \times 10^4$ $L_\odot$ or roughly the Eddington limit for a 1 solar mass white dwarf. OS And maintained a constant bolometric luminosity for 10 days after maximum light in V. After that time, the contribution from emission lines formed outside of the model atmosphere becomes significant and the bolometric luminosity calculated from our model atmospheres drops.

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**Table 1.** Basic Parameters of OS And 86

| Parameter | Value |
|---|---|
| Date discovered | Dec. 5th, 1986 (IAUC 4281) |
| Equatorial Coordinates (1950) | $\alpha = 23^h\ 9^m\ 47.^s72$ $\delta = +47^\circ\ 12'\ 0.''8$ IAUC 4282) |
| Galactic Coordinates | $l = 106.^\circ05$ $b$ = -12.°12 |
| Date of $V_{max}$ and value | 6.3 on 1986 December 8 (IAUC 4283) |
| B-V at Maximum | +0.41 (IAUC 4283) |
| V band at 15 days after maximum | 9 |
| $t_2$ time | 8 ± 1 days |
| $t_3$ time | 20 ± 1 days |
| Speed Class (Payne-Gaposchkin 1957) | Fast |
| Velocity of Expansion | 1200 km $s^{-1}$ (IAUC 4289) |
| Underlying White Dwarf type | Carbon-Oxygen |
| White Dwarf Mass | 0.9 ± 0.2 $M_\odot$ |
| Mean E(B-V) | 0.25 ± 0.05 |
| $M_{0,V}$ | -8.0 ± 0.7 |
| Distance | 5.1 ± 1.5 kpc |
| Scale height | 1.1 ± 0.3 kpc |

**Table 2.** Components of the *IUE* Spectra

| Date | spectrum number | time (UT) | exposure time (s) | spectrum range (nm) | Observed flux (ergs $s^{-1}$ $cm^{-2}$) |
|---|---|---|---|---|---|
| Dec 9, 1986 | LWP9668 | 25:52 | 30 | 200-330 | 3.6e-9 |
| | SWP29836 | 23:00 | 600 | 117-195 | 2.0e-10 |
| Dec 11, 1986 | LWP9682 | 03:54 | 20 | 261-330 | 3.4e-9 |
| | LWP9681 | 02:15 | 60 | 200-261 | 1.0e-9 |
| | SWP29852 | 03:38 | 300 | 117-195 | 5.2e-10 |
| Dec 13, 1986 | LWP9708 | 22:51 | 20 | 261-330 | 3.9e-9 |
| | LWP9709 | 23:55 | 40 | 200-261 | 1.6e-9 |
| | SWP29875 | 22:56 | 120 | 117-195 | 1.3e-9 |
| Dec 16, 1986 | LWP9718 | 23:16 | 20 | 200-330 | 4.2e-9 |
| | SWP29894 | 22:13 | 240 | 117-195 | 1.8e-9[a] |
| Dec 27, 1986 | LWP9794 | 01:56 | 15 | 270-330 | 1.4e-9 |
| | LWP9795 | 03:00 | 70 | 200-270 | 1.6e-9 |
| | SWP29980 | 02:53 | 90 | 117-195 | 2.7e-9 |
| Jan 4, 1987 | LWP9857 | 19:43 | 15 | 270-330 | 3.9e-10 |
| | LWP9858 | 20:44 | 120 | 200-270 | 5.8e-10 |
| | SWP30021 | 19:48 | 60 | 117-195 | 1.2e-9 |

[a] Flux is a lower limit.

**Table 3.** Emission lines present during the "prenebular" phase

| λ(Å) | Identification | Comments |
|---|---|---|
| 1304 | O I | |
| 1335 | C II | |
| 1358 | O I] | |
| 1402 | O IV] | weak |
| 1411 | N I | |
| 1493 | N I | |
| 1550 | C IV | weak |
| 1640 | He II | |
| 1666 | O III] | weak |
| 1743 | N I | blend |
| 1750 | N III] | blend |
| 1907 | C III] | |
| 2145 | N II] | |
| 2322 | [O III] | weak?/blend |
| 2327 | C II] | blend |
| 2471 | [O II] | weak |
| 2800 | Mg II | |